

# Modifications to the pulsar kick velocity due to magnetic interactions in dense plasma

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In this work we have studied the non-Fermi liquid (NFL) behavior that enters into the expression of the pulsar kick velocity of the neutron star composed of degenerate quark matter core. We have incorporated leading order (LO) and next to leading order (NLO) corrections to the velocity and compared the results with the Fermi liquid case. Results for large magnetic field case persistent in neutron stars are also presented. The relation between radius and temperature has been shown with different values of the kick velocity with and without NFL corrections.

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## I. INTRODUCTION

Exploration of the phenomenon of pulsar kicks i.e. the observed large escape velocities of neutron stars (NS) out of supernova remnants has drawn significant attention in recent years [1–5]. Understanding the origin of such high velocities, the so called kick velocities and its connection with pulsar spin has been the subject of many theoretical models. These include postnatal electromagnetic boost and hydrodynamical instabilities in the collapsed supernova to mention a few [6, 7]. However, one of the most natural explanations for these large escape velocities is due to anisotropic neutrino emission from quark matter present at the core of the NS. It is well known that neutrinos carry away almost all of the energy released during the supernova and following proto-neutron star evolution. Thus an asymmetry of roughly about 3 percent in neutrino momentum will be sufficient enough to generate such phenomenal velocities [8]. For a NS with quark matter core in normal phase, the main mechanism of neutrino emission has been the quark direct and inverse URCA processes given by [3, 9],

$$d \rightarrow u + e^- + \bar{\nu}_e \quad (1)$$

$$u + e^- \rightarrow d + \nu_e. \quad (2)$$

The above two reactions, in presence of a strong magnetic field can give rise to asymmetric neutrino emission as explained in [8, 10]. The underlying mechanism for this is the possible polarisation of the electrons leading to neutrino emission in a preferred direction. For this to happen, the magnetic field strength has to be equal to or greater than some critical value which is given as  $B_{crit} = m_i^2 c^3 / (q_i \hbar)$ , where  $m_i$  and  $q_i$  are the mass and charge of the corresponding particle. Thus, we can easily compute that  $B_{crit}^e \sim 4.4 \times 10^{13} G$  and  $B_{crit}^q \sim 10^2 \times B_{crit}^e G$  i.e. the value of the critical magnetic field for electron and quark system respectively. Such strong magnetic field forces the electrons to occupy the lowest Landau level polarising the electron spin opposite to the direction of the magnetic field. This leads to the formation of the neutrino and anti-neutrino emission cones which give rise to polarised neutrino emission along the axis opposite to the magnetic field direction.

The electron polarisation for different conditions of magnetic field and kick velocities has been studied recently by Sagert et. al.[8]. In this work, the authors have discussed pulsar acceleration mechanism based on asymmetric neutrino emission from quark direct URCA process in the core of the NS. Here the dependence of the kick velocity with the quark phase temperature and radius of the star with varying quark chemical potentials has been studied.

One of the interesting development in recent years has been the study of the non-Fermi liquid (NFL) behavior, of quantities like neutrino emissivity [11, 12], mean free path (MFP)[11, 13] or the specific heat [14, 15] of the dense quark matter which significantly modifies the initial cooling rate of the NS via neutrino emission. The NFL effects are dominant in the relativistic regime driven by transverse or magnetic interactions which in the non-relativistic limit is  $\beta = v/c$  suppressed [14]. Infact the quark dispersion relation in dense plasma changes significantly in presence of magnetic interactions mediated by exchange of transverse gluons [16, 17]. It is also known, that the quasiparticle decay width which is given by the imaginary part of the quark self-energy also receives leading order (LO) corrections via the transverse interactions while the electric interactions mediated by the longitudinal gluon exchange contributes to the higher order. Furthermore, the damping rate ( $\gamma$ ) in such a plasma also goes as  $\gamma \sim (E - \mu)$ , where  $E$  is the energy of the quasiparticle and  $\mu$  is the corresponding chemical potential. It is to be noted that in the non-relativistic plasma,  $\gamma \sim (E - \mu)^2$  [16, 17]. The quark self energy has been calculated recently both for the case of zero and low temperature by involving corrections up to next to leading order (NLO) terms which modifies the quark dispersion relation appreciably [18]. Accordingly some of the physical quantities, like heat capacity, pressure are also modified [15]. In many calculations, such corrections appear in the modification of the phase space giving rise to appreciable contributions to the well known Fermi liquid (FL) terms. Such corrections are already been seen to be important resulting in enhanced neutrino emission from dense quark matter [11, 12]. The cooling behavior of NS with quark matter has also been studied recently by several authors [3, 11, 12]. In all these cases, the correction at the LO has been seen to involve  $T \ln(1/T)$  term which has been dubbed as anomalous corrections in many of the recent literatures [14, 17, 18]. Similar behavior has also been reported while investigating quantities like drag, diffusion coefficients and thermal relaxation time of electrons for relativistic degenerate plasmas [19–21].

It is in this context, we revisit the problem of the calculation of the kick velocity to see whether such NFL corrections are significant to alter the kick velocity compared to the FL results.

The plan of the paper is as follows. In section II we discuss the formalism to calculate the kick velocity and calculate the velocity for different conditions of the magnetic field. We present the results in section III followed by conclusion in section IV.

## II. FORMALISM

Neutron star is composed mainly of neutrons with a fraction of protons. Proton fraction may depend on various models. In presence of magnetic field, the proton fraction may increase [22]. We, however focus on the core of the NS where the density is expected to be so high that the relevant degrees of freedom may be considered to be quarks rather than hadrons. The pulsar kick velocity can be calculated if the luminosity, radius of the NS and the neutrino emissivity is known. The emissivity is related, as we shall see, with the specific heat of the core. Initially, total neutrino luminosity ( $L$ ) can be approximated as [8],

$$L \simeq \frac{4}{3}\pi R^3 \epsilon \quad (3)$$

where  $R$  is the radius of the NS and  $\epsilon$  is the neutrino emissivity. Thus, due to momentum conservation we have,

$$\frac{dv}{dt} M_{NS} = \chi L \quad (4)$$

In the above expression, the polarisation fraction of the electrons has been denoted by  $\chi$  and mass of the NS by  $M_{NS}$ . Therefore the kick velocity can be written as [8],

$$dv = \frac{\chi}{M_{NS}} \frac{4}{3}\pi R^3 \epsilon dt \quad (5)$$

Using the cooling equation,

$$C_v dT = -\epsilon dt \quad (6)$$

one can rewrite Eq.5 in terms of the specific heat of the quark matter core. In the region of low temperature and high chemical potential, the Fermi liquid expression of the specific heat of quark is given as [14],

$$C_v|_{FL} = \frac{N_c N_f}{3} \mu_q^2 T \quad (7)$$

where  $N_c$  and  $N_f$  are the number of color and flavor factors respectively. Thus the Fermi liquid contribution to the pulsar kick velocity as reported in [8] can be recast into the following form,

$$v|_{FL} \simeq \frac{8.3 N_c N_f}{3} \left( \frac{\mu_q}{400 \text{ MeV}} \frac{T}{1 \text{ MeV}} \right)^2 \left( \frac{R}{10 \text{ km}} \right)^3 \frac{1.4 M_\odot}{M_{NS}} \chi \frac{\text{km}}{s} \quad (8)$$

The calculation of such kick velocity performed so far is restricted to the Fermi liquid results [8]. Currently, however it is shown in a series of works that NFL behavior arising out of magnetic interactions in the relativistic regime can contribute significantly and wins over the electric or Coulombic interaction for the case of ultradegenerate matter as mentioned in the introduction. In general, in a medium the quark dispersion relation can be obtained by solving the following equation [17],

$$\omega = (E_{p(\omega)} + \text{Re}\Sigma(\omega, p(\omega))) \quad (9)$$

where the  $\Sigma$  represents one loop quark quasiparticle self energy. Explicitly for excitation near the Fermi surface this has been derived in [17, 18],

$$\begin{aligned} \Sigma(\omega) \simeq & -g^2 C_F m \left\{ \frac{\epsilon}{12\pi^2 m} \left[ \log \left( \frac{4\sqrt{2}m}{\pi\epsilon} \right) + 1 \right] + \frac{i\epsilon}{24\pi m} + \frac{2^{1/3}\sqrt{3}}{45\pi^{7/3}} \left( \frac{\epsilon}{m} \right)^{5/3} (\text{sgn}(\epsilon) - \sqrt{3}i) \right. \\ & + \frac{i}{64\sqrt{2}} \left( \frac{\epsilon}{m} \right)^2 - 20 \frac{2^{2/3}\sqrt{3}}{189\pi^{11/3}} \left( \frac{\epsilon}{m} \right)^{7/3} (\text{sgn}(\epsilon) + \sqrt{3}i) \\ & \left. - \frac{6144 - 256\pi^2 + 36\pi^4 - 9\pi^6}{864\pi^6} \left( \frac{\epsilon}{m} \right)^3 \left[ \log \left( \frac{0.928m}{\epsilon} \right) - \frac{i\pi \text{sgn}(\epsilon)}{2} \right] + \mathcal{O} \left( \left( \frac{\epsilon}{m} \right)^{11/3} \right) \right\}. \end{aligned} \quad (10)$$

Here  $\epsilon = \omega - \mu_q \sim T$ ;  $\omega$  being the quasiparticle energy;  $m^2 = (N_f g^2 \mu_q^2)/(4\pi^2)$  and is related to the Debye screening mass by  $m^2 = m_D^2/2$ . In the above calculation of the quark self energy, the dominant contribution at one loop order arises when the gluon in the loop is soft ( $\sim g\mu$ ) as shown in Fig.1 [23]. This approach requires dressing of the gluon propagator to incorporate Debye screening and Landau damping [16, 17]. This modification to the in-medium dispersion relation results in a modified phase space which is responsible for appreciable corrections in all the cases

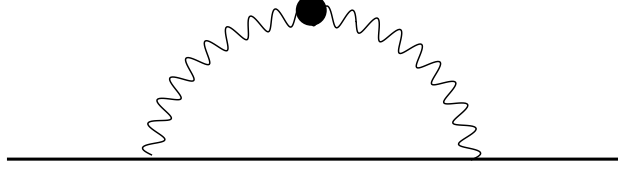


FIG. 1. Quark self-energy with resummed gluon propagator.

including the specific heat of the degenerate quark core. Thus the specific heat of the degenerate quark matter up to NLO is given by [14, 15],

$$C_v|_{total} = C_v|_{FL} + C_v|_{LO} + C_v|_{NLO} \quad (11)$$

where,

$$C_v|_{LO} = N_g \frac{g_{eff}^2 \mu_q^2 T}{36\pi^2} \left( \ln \left( \frac{4g_{eff} \mu_q}{\pi^2 T} \right) + \gamma_E - \frac{6}{\pi^2} \zeta'(2) - 3 \right) \quad (12)$$

and

$$C_v|_{NLO} = N_g \left[ -40 \frac{2^{2/3} \Gamma(\frac{8}{3}) \zeta(\frac{8}{3})}{27\sqrt{3}\pi^{11/3}} T^{5/3} (g_{eff} \mu_q)^{4/3} + 560 \frac{2^{1/3} \Gamma(\frac{10}{3}) \zeta(\frac{10}{3})}{81\sqrt{3}\pi^{13/3}} T^{7/3} (g_{eff} \mu_q)^{2/3} \right. \\ \left. + \frac{2048 - 256\pi^2 - 36\pi^4 + 3\pi^6}{180\pi^2} T^3 \left[ \ln \left( \frac{g_{eff} \mu_q}{T} \right) + \bar{c} - \frac{7}{12} \right] \right] \quad (13)$$

where the coupling constant  $g$  is related to  $g_{eff}$  as,

$$g^2 = \frac{2 g_{eff}^2}{N_f}, \quad (14)$$

and  $C_v|_{total}$  is the sum of the FL, LO and NLO contribution to the specific heat of the quark matter. Thus we obtain the LO contribution to the kick velocity as,

$$v|_{LO} \simeq \frac{16.6 N_C N_f}{3} (C_F \alpha_s) \left( \frac{\mu_q}{400 \text{ MeV}} \frac{T}{1 \text{ MeV}} \right)^2 \left( \frac{R}{10 \text{ km}} \right)^3 \frac{1.4 M_\odot}{M_{NS}} \chi \left[ c_1 + c_2 \ln \left( \frac{g \mu_q \sqrt{N_f}}{T} \right) \right] \frac{km}{s} \quad (15)$$

where  $C_F = (N_c^2 - 1)/(2N_c)$  and the constants are  $c_1 = -0.13807$  and  $c_2 = 0.0530516$ . Now we have also extended our calculation beyond the LO in NFL correction. The NLO correction to the pulsar kick velocity is obtained as,

$$v|_{NLO} \simeq \frac{16.6 N_C N_f}{3} \left( \frac{\mu_q}{400 \text{ MeV}} \frac{T}{1 \text{ MeV}} \right)^2 \left( \frac{R}{10 \text{ km}} \right)^3 \frac{1.4 M_\odot}{M_{NS}} \chi(C_F \alpha_s) \\ \times \left[ a_1 \left( \frac{bT}{\mu_q} \right)^{2/3} + a_2 \left( \frac{bT}{\mu_q} \right)^{4/3} + \left[ a_3 + a_4 \ln \left( \frac{\mu_q}{bT} \right) \right] \left( \frac{bT}{\mu_q} \right)^2 \right] \frac{km}{s} \quad (16)$$

where the constants are evaluated as,

$$a_1 = -\frac{12\pi \times 0.04386}{8}; a_2 = \frac{12\pi \times 0.04613}{10}; a_3 = -2.4162; a_4 = -0.4595 \quad (17)$$

and

$$b = \frac{2\pi}{\sqrt{N_f} g}. \quad (18)$$

The net contribution to the pulsar kick velocity upto NLO is obtained by the sum of the Fermi liquid result and the non-Fermi liquid correction upto NLO:

$$v|_{total} = v|_{FL} + v|_{LO} + v|_{NLO} \quad (19)$$

The long range magnetic interactions lead to an anomalous  $T^2 \ln T^{-1}$  term in the expression of the pulsar kick velocity. The specific heat of the quark matter is modified due to strong magnetic field present at the core of the NS. However it has been found that the effect of such high magnetic field is insignificant compared to the NFL corrections to the specific heat of the degenerate quark matter core in this temperature regime.

### A. Pulsar kick for the case of small magnetic field

In presence of magnetic field ( $B$ ) the number density of electrons is given by:

$$n_{\mp} = \frac{geB}{(2\pi)^2} \sum_{\eta} \int_0^{\sqrt{\mu_e^2 - m_e^2 - 2\eta eB}} dp_z. \quad (20)$$

The number of Landau levels is limited to  $\eta_{max} = \frac{\mu_e^2 - m_e^2}{2eB}$ . For the case of  $(\mu_e^2 - m_e^2) \gg 2eB$ , the number of occupied Landau levels is large. Thus we obtain, for the case of vanishing temperature (cold neutron stars), the electron spin polarisation is [8],

$$\chi \simeq \frac{3}{2} \frac{m_e^2}{\mu_e^2 - m_e^2} \left( \frac{B}{B_{cr}^e} \right) \quad (21)$$

where the critical value of the magnetic field is given by  $B_{cr}^e \simeq 4.4 \times 10^{13} G$ . Thus including the effect of electron spin polarisation on the FL contribution to the kick velocity, Eq.(8) is modified as,

$$v|_{FL} \simeq \frac{8.3N_C N_f}{2} \left( \frac{\mu_q}{400 MeV} \frac{T}{1 MeV} \right)^2 \left( \frac{R}{10 km} \right)^3 \frac{1.4 M_{\odot}}{M_{NS}} \left( \frac{m_e^2}{\mu_e^2 - m_e^2} \frac{B}{B_{cr}^e} \right) \frac{km}{s} \quad (22)$$

The LO contribution to the kick velocity is given by,

$$v|_{LO} = \frac{16.6N_C N_f}{2} (C_F \alpha_s) \left( \frac{\mu_q}{400 MeV} \frac{T}{1 MeV} \right)^2 \left( \frac{R}{10 km} \right)^3 \frac{1.4 M_{\odot}}{M_{NS}} \left( \frac{m_e^2}{\mu_e^2 - m_e^2} \frac{B}{B_{cr}^e} \right) \left[ c_1 + c_2 \ln \left( \frac{g\mu_q \sqrt{N_f}}{T} \right) \right] \frac{km}{s}. \quad (23)$$

We have also extended our calculation beyond the LO in NFL correction. The NLO correction to the pulsar kick velocity turns out to be,

$$\begin{aligned} v|_{NLO} \simeq & \frac{16.6N_C N_f}{2} \left( \frac{\mu_q}{400 MeV} \frac{T}{1 MeV} \right)^2 \left( \frac{R}{10 km} \right)^3 \frac{1.4 M_{\odot}}{M_{NS}} \left( \frac{m_e^2}{\mu_e^2 - m_e^2} \frac{B}{B_{cr}^e} \right) (C_F \alpha_s) \\ & \times \left[ a_1 \left( \frac{bT}{\mu_q} \right)^{2/3} + a_2 \left( \frac{bT}{\mu_q} \right)^{4/3} + \left[ a_3 + a_4 \ln \left( \frac{\mu_q}{bT} \right) \right] \left( \frac{bT}{\mu_q} \right)^2 \right] \frac{km}{s}. \end{aligned} \quad (24)$$

The total velocity is given by Eq.(19).

### B. Pulsar kick for the case of large magnetic field

In this section the magnetic field strength is chosen to be much larger than the temperature, the chemical potential as well as the electron mass ( $\mu_e, m_e, T \ll \sqrt{2eB}$ ). The number density in this case is given by,

$$n_{\mp} = \frac{eB}{(2\pi)^2} \sum_{\eta} \int_0^{\infty} dp \frac{1}{e^{\sqrt{p^2 + 2\eta eB}/T} + 1}, \quad (25)$$

The electron polarisation is given as [8],

$$\chi \sim 1 - \frac{4}{\ln(2)} \sqrt{\frac{\pi T}{2\sqrt{2eB}}} e^{-\sqrt{2eB}/T}. \quad (26)$$

Thus, the pulsar kick velocity is obtained as,

$$v|_{FL} = \frac{2N_c N_f \pi}{9} \left( \frac{\mu_q^2 R^3}{M_{NS}} \right) \left[ T^2 - \frac{2^{9/4}}{\ln(2)} \sqrt{\frac{\pi}{eB}} \int T^{3/2} e^{-\sqrt{2eB}/T} dT \right] \quad (27)$$

The LO contribution to the pulsar kick velocity is obtained as,

$$v|_{LO} = \frac{4N_c N_f}{27} \left( \frac{\mu_q^2 R^3}{M_{NS}} \right) (C_F \alpha_s) \left[ \int T \ln \left( \frac{0.04g\mu_q \sqrt{N_f}}{T} \right) dT - \frac{2^{5/4}}{\ln(2)} \sqrt{\frac{\pi}{eB}} \int T^{3/2} \ln \left( \frac{0.04g\mu_q \sqrt{N_f}}{T} \right) e^{-\sqrt{2eB}/T} dT \right] \quad (28)$$

The NLO contribution to the kick velocity is obtained as,

$$v|_{NLO} = \left( \frac{4}{3} \pi \frac{R^3}{M_{NS}} \right) \int \chi(T) C_v(T) |_{NLO} dT \quad (29)$$

The above equations have to be solved numerically. The numerical estimation has been presented in fig.[5]. The total kick velocity up to NLO is given as the sum of the FL, LO and NLO contribution to the kick velocity.

### III. RESULTS AND DISCUSSIONS

An estimation of the radius of the NS as a function of temperature (R-T relationship) has been presented in this section for different kick velocities and different conditions of magnetic field in NS. For this purpose, we have assumed the quark chemical potential to be  $400 \text{ MeV}$  with temperature ranging from  $0.1$  to  $5 \text{ MeV}$ . Our parameters are in good agreement with the high baryon density prevalent at the core of the NS. In addition, we have taken  $\alpha_s = 0.5$  and  $\mu_e = 10 \text{ MeV}$  [8]. The pulsar mass has been taken to be  $1.4 M_\odot$  (where  $M_\odot = 2 \times 10^{30} \text{ kg}$  is the mass of the Sun). As high magnetic fields are persistent in the core of the NS, we have taken magnetic fields of  $\sim 10^{16} \text{ G}$  or higher relevant to the corresponding cases. In writing Eq.(8), we purposely ignore the effect of magnetic field on  $C_v$  [8]. It has been seen that the effect of the magnetic field on  $C_v$  is rather small compared to the result without the magnetic field.

In the left panel of Fig.2 we observe that there is a considerable decrease in the radius of the NS with the inclusion of the LO correction over the FL case. This entails a significant increment of the kick velocity for a given temperature due to NFL correction. We have obtained the result considering fully polarised electrons, thus making the electron polarisation fraction ( $\chi$ ) equal to unity. We have plotted the R-T behavior for two values of the kick velocities i.e.  $1000 \text{ km/s}$  and  $500 \text{ km/s}$ . In the right panel of Fig.2 we have presented the R-T comparison for the case of partially polarised electrons. In this case, the electron polarisation fraction  $\chi$  is less than unity.

In Fig.3 the left panel shows the comparison between the FL, LO and NLO result for the radius and temperature dependence for the case of fully polarized electrons for kick velocities of  $1000 \text{ km/s}$ . The right panel shows similar comparison for kick velocity of  $500 \text{ km/s}$ .

The left panel of Fig.4 shows the comparison between the FL, LO and NLO result for the radius and temperature dependence for the case of partially polarized electrons for kick velocities of  $1000 \text{ km/s}$ . The right panel shows similar comparison for kick velocity of  $500 \text{ km/s}$ . The LO correction lowers the radius of the NS for a specific value of temperature. We have found out that the NLO results impose a slight correction to the LO results in both Fig.3 and Fig.4.

Fig.5 shows for a large value of magnetic field, we have generated the plot numerically as this case is too complicated to be solved analytically. We have found that there is an appreciable change of the  $R - T$  relationship of the NS due to LO. However, the NLO correction to the kick velocity does not show considerable change from the LO result as evident from the graphs.

### IV. CONCLUSION

In this work, we have derived the expressions of the pulsar kick velocity including the NFL corrections to the specific heat of the degenerate quark matter core. The contributions from the electron polarization ( $\chi$ ) for different cases has also been taken into account to calculate the velocities. In addition, comparison has been made between the NFL LO and NLO contributions to the kick velocity with the FL case. We have found that the NFL LO contributions are significant while calculating the radius-temperature relationship as seen from the graphs presented for the case of the neutron star with moderate and high magnetic field. The anomalous corrections introduced to the pulsar kick

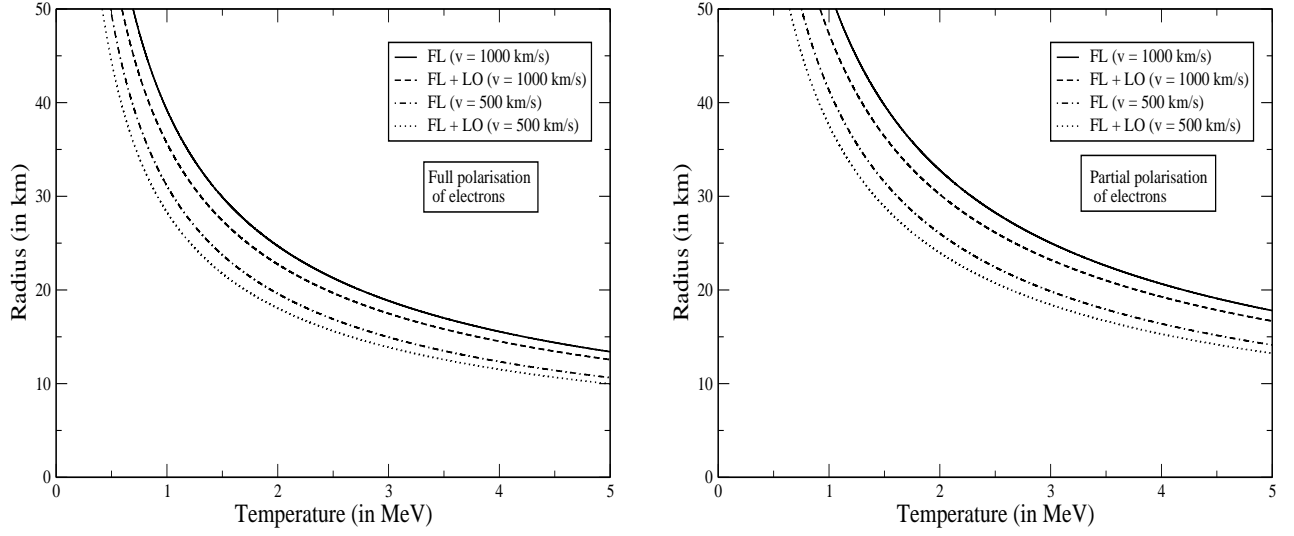


FIG. 2. The left panel shows the comparison between the FL and NFL LO result for the radius and temperature dependence for the case of fully polarised electrons. The right panel shows similar comparison for partially polarised electrons. The graphs have been plotted for kick velocities of  $1000 \text{ km/s}$  and  $500 \text{ km/s}$  for both the cases.

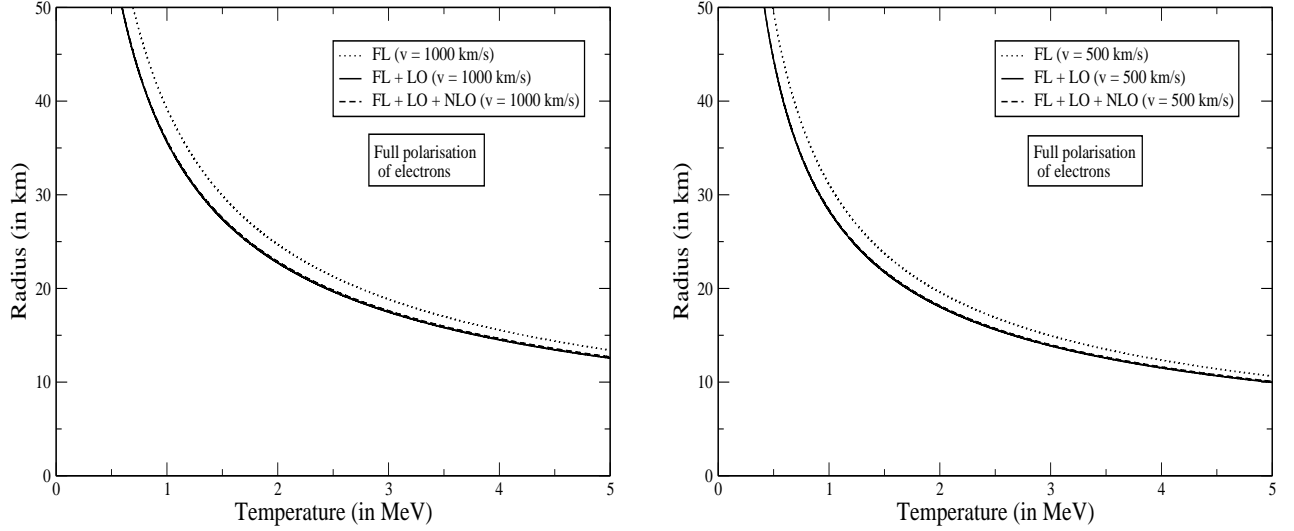


FIG. 3. The left panel shows the comparison between the FL, NFL LO and NFL NLO result for the radius and temperature dependence for the case of fully polarized electrons for kick velocities of  $1000 \text{ km/s}$ . The right panel shows similar comparison for kick velocity of  $500 \text{ km/s}$ .

velocity due to the NFL (LO) behavior increases appreciably the kick velocity for a particular value of radius and temperature. However, for all the cases, no appreciable change in the R-T relationship has been observed for the NLO correction with respect to the LO case.

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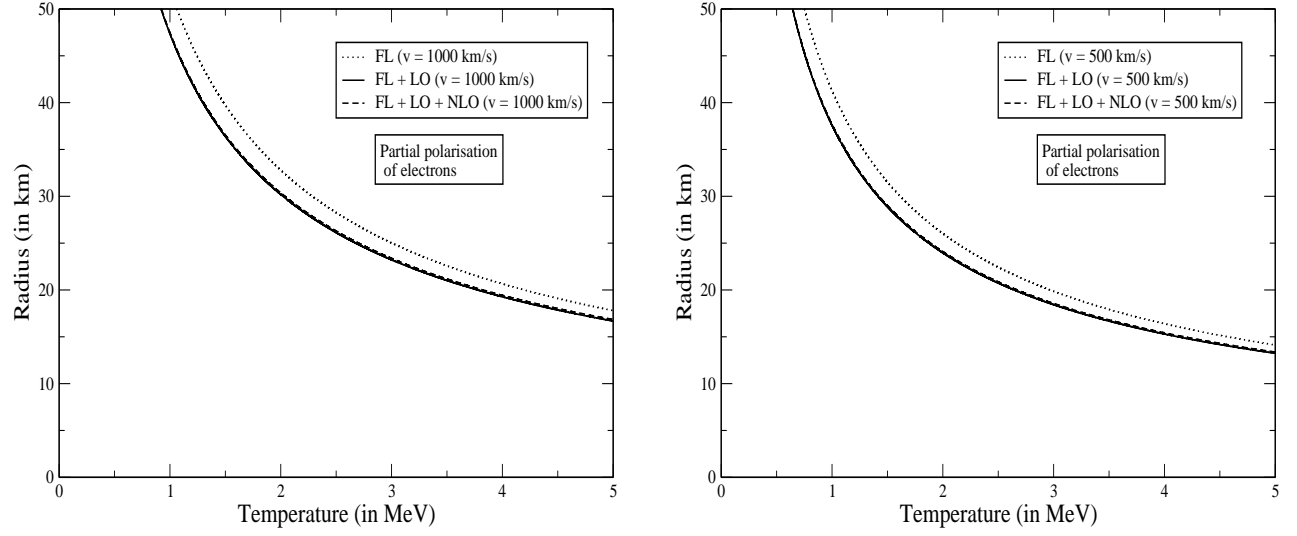


FIG. 4. The left panel shows the comparison between the FL, NFL LO and NFL NLO result for the radius and temperature dependence for the case of partially polarized electrons for kick velocities of  $1000 \text{ km/s}$ . The right panel shows similar comparison for kick velocity of  $500 \text{ km/s}$ .

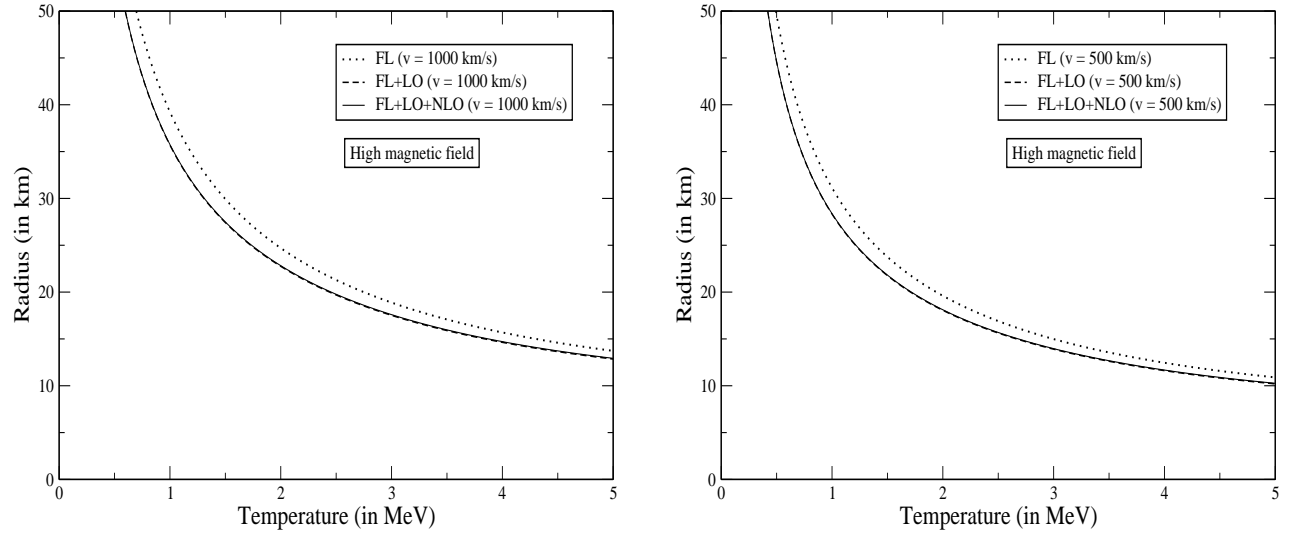


FIG. 5. The left panel shows the numerical comparison where high magnetic field has been taken into account along with vanishing temperature for kick velocity of  $1000 \text{ km/s}$ . The right panel shows similar comparison for kick velocity of  $500 \text{ km/s}$ .

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